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The Influence of Social and Environmental Factors on Dust Lead, Hand Lead, and Blood Lead Levels in Young Children[1]

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The roles of environmental and behavioral factors in determining blood lead levels were studied in a cohort of young children living in an urban environment. The subjects were observed at 3-month intervals from birth to 24 months of age. Repeated measurements were made of the children's blood lead levels, environmental levels of lead in house dust, and in the dust found on the children's hands. A qualitative rating of the residence and of the socioeconomic status of the family was obtained. Interviews and direct observation of parent and child at home were used to evaluate various aspects of caretaker–child interactions. Data analysis consisted of a comparison of results obtained by (a) simple correlational analysis, (b) multiple regression analysis, and (c) structural equations analysis. The results demonstrated that structural equation modeling offers a useful approach to unraveling the complex interactions present in the data set. In this preliminary analysis, the suspected relationship between the levels of lead in house dust and on hands and the blood lead level was clearly demonstrated. Furthermore, the analyses indicated an important interplay between environmental sources and social factors in the determination of hand lead and blood lead levels in very young children. © 1985 Academic Press, Inc.

INTRODUCTION

Childhood lead exposure is a multivariate problem with the effects of multiple sources of lead being mediated by multiple sociodemographic factors. While there have been numerous studies reporting the individual influence of various factors on blood lead (PbB) levels (Stark *et al.*, 1978; Stark *et al.*, 1982), few have addressed the multivariate aspects of the problem (Angle and McIntire, 1979; Yankel *et al.*, 1977). Fewer still have measured, with equal precision, these environmental and sociodemographic factors within the same study cohort (Charney *et al.*, 1980).

Previous studies in this area have used a variety of data analytic techniques to explore associations and identify causal agents. These techniques range from categorical (χ^2) analyses (Stark *et al.*, 1978) to analyses which take into account the interdependence of the independent variables (multiple regression) (Yankel *et al.*, 1977). While the multiple regression approach can be used to maximize the variance accounted for with the most parsimonious set of predictors, it often

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contributes little to our understanding of the underlying structure of interrelationships among a large set of intercorrelated predictor and outcome variables.

It is desirable to employ a statistical method which furthers our understanding of possible causal relationships contained within these complex data sets. One possible approach involves the development of structural equation models or systems models. These techniques have been developed to efficiently deal with (1) intercorrelated sets of dependent and independent variables, and (2) "endogenous" variables which serve as the dependent variable in at least one structural equation and as independent variables in other equations (Bentler, 1980). Although variants of the classical regression model can handle the first situation (e.g., multivariate multiple regression, "step-down" analyses, ridge regression, etc.), the classical techniques do not adequately handle the second situation. However, even the simplest and most familiar technique, i.e., path analysis, has been used mainly by geneticists but rarely if ever applied to an environmental issue. In fact, path analysis is a special case of systems modeling when all parameters (paths) in the model are included in the analysis and their values estimated. Since this approach does not provide a flexible means for eliminating paths with no statistical validity, the path analytic approach is generally not preferred.

The purpose of the present report was twofold: (1) to examine the roles of environmental and behavioral factors in determining blood lead levels in a cohort of young children living in a high lead environment; and (2) to evaluate the utility of structural equation modeling in the context of an environmental health problem. The results reported here should be viewed as preliminary to more extensive analyses which will be reported later.

METHODS

Subjects. The data presented in this report were derived from a subset of children participating in a large prospective study of childhood lead exposure and its effects on child development. The sample was restricted to those children for whom we currently have complete data with respect to blood lead levels, measures of lead in the home environment, measures of the quality of caretaking, and characterization of the quality of the housing occupied by the subjects during the study interval. In addition, the analyses were restricted to children less than or equal to 24 months of age due to the limited amount of data currently available for children over 24 months of age. The first environmental assessments took place when the children were about 9 months of age, thereby restricting the analyses to children 9 months of age and older. Data from approximately 45 children were available for analysis. Further description of the full study cohort has been reported elsewhere (Bornschein *et al.*, 1985).

Blood lead determinations. Blood samples were obtained by venipuncture. All analyses were performed in duplicate. Lead was measured by anodic stripping voltammetry (ASV) with the use of an ESA Model 3010A. Our laboratory participates in both the CDC and Pennsylvania blood lead proficiency programs. Blind and known, "bench-top," quality-control samples were also analyzed with each analytic run. The coefficients of variation for blood lead levels encountered in this report range from 8 to 18%. Further details of analytic procedure and proficiency have been reported (Bornschein *et al.*, 1985; Que Hee, *et al.*, 1985).

Environmental sampling and analysis. Environmental sampling was carried out when the children were about 7 and 19 months of age. If the child changed residences during the study interval, an additional assessment was carried out in the new residence. If data from two environmental visits to the same residence were available, the data were averaged to obtain a single set of environmental data for each residence. Interior surface dust was collected by three sweeps of a defined area using a 2-liter/min vacuum (personal air sampler). Recovery studies have shown that this procedure yields a reliable and high mean recovery rate (84 ± 4%) from a variety of surface types (Que Hee *et al.*, 1985).

Lead was recovered from the surface of the child's hands by repeated wipings of both hands with a total of six wet wipes (Walgreen's Brand Wet Wipes). Recovery studies were undertaken to examine the influence of towel type and number of wipes on recovery of known amounts of lead applied to the subject's hands. The procedure chosen yielded a mean recovery rate of 84 ± 7% (Que Hee *et al.*, 1985).

Housing evaluations. All dwellings occupied by study participants were evaluated with respect to (a) *age* of dwelling (19th century, 20th century–pre-World War II, or 20th century–post-World War II, (b) *condition* of dwelling (satisfactory, deteriorating, or dilapidated), and (c) *type* of dwelling (public housing, rehabilitated housing, and nonpublic/nonrehabilitated housing). A more detailed description of procedures, operational definitions, and housing stock occupied by study residences has been reported (Clark *et al.*, 1985). Previous preliminary analyses have shown high correlations between this qualitative evaluation of housing, interior lead levels, and child's blood lead level (Hammond *et al.*, 1985). Two observers independently evaluated each resident. Interobserver agreement exceeded 90% on all items ($r > 0.90$).

Social measures. The Home Observation for Measurement of the Environment (HOME) (Caldwell and Bradley, 1978) was used at 6, 12, and 24 months to quantitate various aspects of the child's rearing environment. Two trained observers attended and independently scored each home visit. Interobserver agreement exceeded 95% on all items ($r > 0.95$).

Determination of the socioeconomic status (SES) of the families was made through use of the Hollingshead Four-Factor Scale (Hollingshead, 1975). This scale was administered at 3 and 15 months.

Criteria for selection of variables. Our central hypothesis predicted that lead in house dust (PbD) influenced blood lead (PbB) with hand-to-mouth activity being a significant route of exposure. Thus hand lead (PbH), PbD, and PbB were included in all models. Quality of rearing environment, socioeconomic status of the parents, and quality of housing were predicted to have important influences on this route of exposure and were thus included. Many other variables obviously can influence PbB and could have been incorporated into these analyses. However, these analyses were viewed as exploratory. Furthermore, an equally important objective was to examine various data-analytic procedures on a relatively well-defined, simple data set. Therefore, other predictors and modifiers of lead exposure were excluded from consideration at this time. A summary of the main variables and subscales included in the analyses is shown in Table 1.

Data analysis. Prior to data analysis, all lead measures, i.e., blood lead, dust lead, and hand lead values, were subjected to $\log_e$ transformation to obtain approximate normality of their distributions. Analyses were conducted with the use of the CORR procedure (for Pearson product–moment correlation coefficients) and the first stage of the SYSREG procedure (to obtain ordinary least-squares regressions) which are part of the SAS statistical package (Barr *et al.*, 1976). The structural equations model was estimated via the third stage of SYSREG (Zellner, 1962). A backward elimination procedure was employed to evolve a final model from the initial, overparameterized structural model. Criteria for elimination of exogenous (predictor) variables included (a) initial elimination of paths with beta weights not in the predicted direction, (b) further elimination of paths (beta weights) which did not attain statistical significance ($P < 0.05$), and (c) final elimination of paths which did not add to the internal consistency of the model across ages (further details appear in the discussion).

RESULTS

Simple correlations. Table 2 summarizes the correlation between PbB and various predictor variables. Correlations tended to be moderately strong and relatively consistent across ages. As predicted, PbD and PbH were significantly correlated with PbB. Likewise, presumed mediating variables such as the total HOME score and three of six HOME subscales were significantly correlated with PbB. Quality of housing and SES were also found to be associated with PbB. This analysis does not estimate, nor control for, the high degree of correlation among these predictor variables.

Multiple regression. Table 3 depicts the result of an ordinary least-squares multiple regression analysis for each age cohort. In this analysis, all possible predictor variables were entered simultaneously. Note the high degree of insta-

TABLE 1

VARIABLES INCLUDED OR EXCLUDED FROM ANALYSES

Endogenous variables:	PbD (ppm)	PbH (μg)	PbB (μg/dl)
Exogenous variables:	HOME scales Variety in daily stimulation Mothers emotional and verbal response Provision of play materials Organization of the environment Avoidance of use of punishment Mothers involvement with child Total HOME score	Housing quality Age (three categories) Type (three categories) Condition (three categories)	SES Scale Parent(s) occupation Parent(s) education
Other variables *not* included in model:	Race Sex Season Interior air lead Exterior soil lead	Interior paint lead Exterior paint lead Prior PbB history Other social variables	

TABLE 2
SIMPLE CORRELATIONS BETWEEN ENVIRONMENTAL OR SOCIAL VARIABLES AND CHILD'S BLOOD LEAD LEVEL

Variable		Child's age (months)					
		9	12	15	18	21	24
	N	41	43	47	47	44	42
Hand lead	*r*	0.44	0.53	0.44	0.51	0.35	0.48
Dust lead	*r*	0.44	0.67	0.54	0.51	0.40	0.43
SES	*r*	−0.30	−0.32	−0.30	−0.37	−0.30	—
HOME (Total score)	*r*	−0.33	−0.46	−0.30	—	—	—
Maternal involvement	*r*	—	−0.37	−0.29	−0.23	—	—
Organization of environment	*r*	−0.41	−0.31	—	—	—	—
Provision of play materials	*r*	—	−0.37	−0.34	−0.29	—	—
Housing							
Type							
Public	*r*	—	—	−0.31	−0.34	−0.43	−0.33
Rehabilitated	*r*	—	—	—	—	—	—
Condition							
Satisfactory	*r*	−0.48	−0.50	−0.39	−0.39	—	—
Deteriorating	*r*	0.42	0.42	0.39	0.38	—	—
Age							
19th century	*r*	0.34	0.37	0.46	0.42	0.56	0.54
20th century	*r*	—	—	—	—	—	—

Note. All reported correlations are significant at $P < 0.05$.

bility of beta weights within a given variable across age cohorts, which is characteristic of an overparameterized model. Ordinarily, the next step in this type of analysis would involve a backward elimination procedure wherein nonsignificant covariates would be sequentially dropped from successive analyses until a final reduced model was attained. This type of analysis can be used to maximize the explained variance with the most parsimonious set of predictors. However, it obscures the underlying structural relations among variables. Furthermore, if separate unweighted regressions were performed for PbD, PbH, and PbB, the estimated beta weights would be biased since the simultaneous nature of the system of equations would not be taken into account.

Structural equations. Figure 1 summarizes the qualitative aspects of this analysis. Figure 1a shows the relationship hypothesized to exist between independent (exogenous) and dependent (indogenous) variables. Figure 1b shows all the relationships that were tested in the course of the analysis, while Fig. 1c shows the relationships found in the analysis. The analysis confirmed the predicted path from housing quality (House) to PbD to PbH to PbB. A second pathway (not predicted) was also detected between PbD and PbB (Fig. 1c). As predicted, one subscale of the HOME (Maternal Involvement with Child) was found to be a significant modifier of PbH. However, unexpectedly, two subscales, Variety in Daily Stimulation and Emotional and Verbal Responsivity of Mother, were found to be associated with PbD. SES was also unexpectedly found to have a small but significant association with PbB.

Quantitative aspects of the final systems model for 18-month-olds are depicted

TABLE 3

ORDINARY LEAST-SQUARES MULTIPLE REGRESSION ESTIMATES FOR EFFECTS ON PbB OF ALL POSSIBLE PREDICTORS

Variable	Child's age (months)					
	9	12	15	18	21	24
Intercept	3.04*	2.06*	1.14	2.60*	3.49*	4.20*
Hand lead	0.13	0.09	0.14	0.16*	0.02	0.09
Dust lead	0.04	0.19	0.16	0.23	0.20	0.15
SES	−0.01	−0.01	−0.02	−0.02*	−0.02*	−0.002
HOME scales						
Maternal involvement with child	0.09	−0.03	−0.13	−0.01	−0.04	−0.01
Variety in daily stimulation	0.03	0.00	0.22	−0.01	−0.01	−0.09
Avoidance of use of punishment	0.05	−0.01	0.07	0.06	−0.06	−0.06
Provision of appropriate play materials	−0.05	−0.04	−0.06	−0.06	−0.05	−0.07
Organization of the physical environment	−0.30	−0.05	−0.09	−0.13	0.05	−0.07
Mother's emotional and verbal responsivity	0.01	0.02	0.07	0.08	0.04	−0.005
Housing						
Type						
Public	0.22	0.14	0.12	0.07	0.17	0.33*
Rehabilitated	0.03	0.11	0.07	−0.04	−0.16	−0.06*
Age						
19th century	0.17	0.01	0.15	0.17	0.51*	0.63
20th century	−0.12	−0.07	0.08	0.004	−0.03*	0.07
Condition						
Satisfactory	−0.14	−0.13	0.05	−0.10	−0.12	−0.28
Deteriorating	0.01	−0.05	0.05	−0.06	−0.11	−0.19
R^2	0.52*	0.66*	0.63*	0.58*	0.61*	0.68*

* $P \leq 0.05$.

in Fig. 2. The values in parentheses are the y intercept in natural log units. The values next to the arrows are the beta weights associated with each particular pathway. The arrows in this diagram or "flowgraph" (Heise, 1975) imply causal ordering of events. However, the analysis does not test directionality of correlated relationships, nor "prove" causality, which is not a statistical issue but rather a logical inference.

Table 4 summarizes the results of the structural equations models for each age cohort. The reported values are path or beta coefficients in the case of the exogenous variables and y intercepts in the case of the three endogenous variables, PbD, PbH, and PbB. Coefficients were found to be remarkably stable across ages both with respect to sign and magnitude of the coefficient. Likewise, the weighted R^2 for the system models were relatively stable, ranging from 0.44 to 0.59.

DISCUSSION

Complex interrelationships among antecedent and outcome variables may be described at various levels of sophistication. The simple correlations may be computed or a series of multiple regressions performed, one for each outcome variable. The correlations of a number of "predictor" variables with PbB were reported (Table 2) for purely descriptive purposes.

As pointed out in the introduction, the technique of calculating multiple regressions with a fully parameterized model is often referred to as "path analysis." However, it is *only* in this situation that this technique results in consistent es-

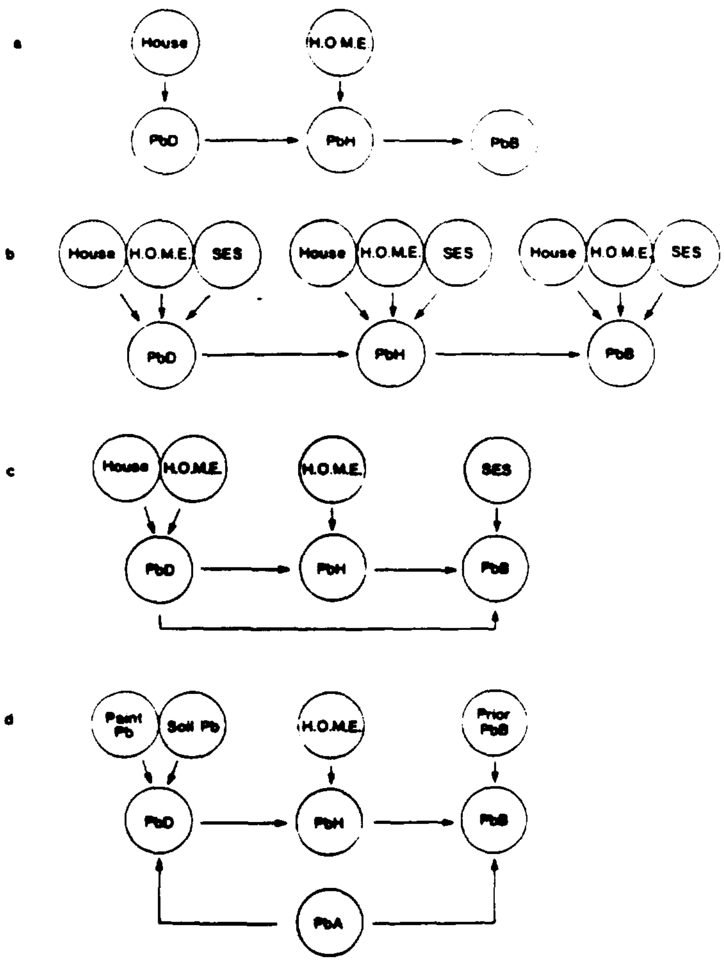

FIG. 1. Flow graphs on path diagrams depicting causal ordering of relationships: (a) hypothesized relationships; (b) relationships tested; (c) relationships found to be statistically significant; (d) model to be tested in next series of analysis. House: age, type, and condition of housing; HOME: Home Observation for Measurement of the Environment; SES: socioeconomic status; PbD: lead content of surface dust (ppm); PbH: lead content of handwipes (μg); PbB: blood lead ($\mu g/dl$); PbA: interior air lead concentration ($\mu g/m^3$).

timates of the parameters (beta or path coefficients). A better and more flexible approach is to recognize the possibility that the equation errors in each of the outcome variables may be correlated, resulting in inconsistent and biased estimates of the effects of the "exogenous" (antecedent or predetermined) variables on the "endogenous" (outcome or dependent) variables. This approach leads to weighting the parameter estimates by the inverse of the covariance among the errors (cf. Zellner, 1962), known in the statistical literature as a "generalized" least-squares (GLS) solution (path analysis and simple multiple regression are examples of "unweighted or ordinary" least squares, or OLS).

It is generally accepted, in the context of simple regression models, that

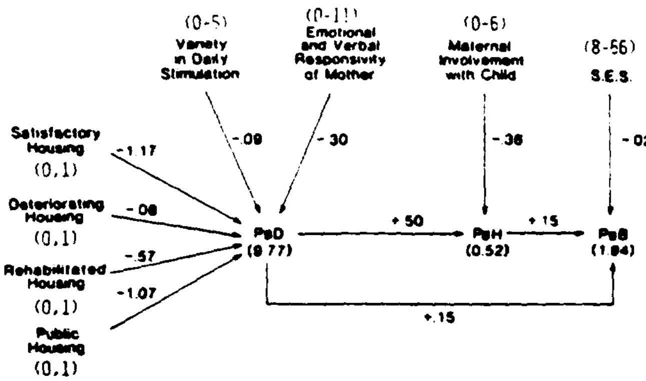

FIG. 2. System model for 18-month-olds indicating the y intercept for endogenous variables ($\log_e$ units) and unstandardized weights (next to arrows). Numbers in parentheses associated with exogenous variables are the range of the scale scores.

$$\text{Log}_e\ \text{PbB} = 1.94 - 0.02\,(\text{SES}) + 0.15\,(\text{PbD}) + 0.15\,(\text{PbH}),$$

where $\log_e$ PbD = 9.77 − 1.07 (public) − 0.57 (rehab.) − 1.17 (satis.) − 0.08 (deterior.) − 0.09 (stimul.) − 0.30 (verbal respons.) and $\log_e$ PbH = 0.52 − 0.36 (maternal invol.) + 0.50 (PbD).

overparameterization leads to poor estimates of both the beta coefficients and the associated standard errors, while allowing too few possible "predictors" to enter a regression equation may lead to the same statistical and also interpretative difficulties. The generally preferred technique is to start from an overparameterized model, with all possible "covariates" included, dropping out those effects which either are suppressed (coefficients in the unhypothesized direction) or do

TABLE 4

INTERCEPTS AND UNSTANDARDIZED BETA WEIGHTS FOR ALL SYSTEMS MODELS

Variable		Child's age (months)					
		9	12	15	18	21	24
	N	41	43	47	47	44	42
Intercepts							
PbD		10.23	10.48	10.07	9.77	10.86	10.34
PbH		0.31	0.12	0.39	0.52	2.41	2.67
PbB		1.71	1.59	2.01	1.94	2.63	1.70
Effects on PbD							
Public housing		−1.26	−1.32	−1.23	−1.07	−0.78	−0.66^a
Rehabilitated housing		−0.50	−0.32	−0.64	−0.57	−0.11	−0.07^a
Satisfactory housing		−1.50	−1.48	−1.03	−1.17	−2.44	−2.45
Deteriorated housing		−0.15	−0.27	−0.02	−0.08	−1.56	−1.77
Variety in daily stimulation		−0.15	−0.14	−0.24	−0.30	−0.29	−0.27^a
Verbal responsivity of mother		−0.16	−0.19	−0.14	−0.09	−0.10	−0.06^a
Effects on PbH							
Maternal involvement with child		−0.32	−0.30	−0.25	−0.36	−0.42	−0.47
PbD		0.49	0.49	0.42	0.50	0.27	0.28
Effects on PbB							
SES		−0.02^a	−0.02	−0.02	−0.02	−0.02	−0.01^a
19th century housing		0.04^a	−0.03^a	0.17^a	0.09^a	0.25	0.22
20th century; Pre-World War II		0.06^a	−0.05^a	0.09^a	0.03^a	0.01	0.10
PbD		0.13	0.19	0.15	0.15	0.06^a	0.13^a
PbH		0.13	0.13	0.14	0.15	0.11^a	0.23
Weighted R^2		0.59	0.59	0.52	0.57	0.44	0.44

^{a} Parameters were *not* statistically significant.

not attain an acceptable magnitude of significance (as measured by a P value). This strategy would also seem to apply in the context of structural equation modeling, when a firm model is unavailable or unknown. In this situation, exogenous variables which show no effect or effects in the illogical direction may be dropped until a final, more parsimonious model is achieved. The effects of endogenous variables on other (later occurring) endogenous variables should not be dropped, especially if this is the "causal" chain of interest. Their statistical significance may be judged in the final model. This procedure generally goes under the rubric of "backward elimination."

The PbD to PbH to PbB path was estimated, beginning with all exogenous variables being allowed to effect all three endogenous variables. By backward elimination, a final model (Fig. 2) with the same exogenous variables included for each (single) equation at each age was estimated. This "systems regression" utilized Zellner's (1962) GLS procedure. To judge the significance of each effect, an alpha level of 0.05 was chosen. The stability of the model, in the age range investigated, was also a guide to retention/elimination of predetermined variables and served as a further check on the convergence to a final model (in the presence of so much confounding).

The results of the systems analysis should be viewed as preliminary findings since the analysis was exploratory in nature. A second confirmatory analysis on a different subset of children drawn from the same cohort will be conducted when more data become available. Nonetheless, the analysis indicates some interesting relationships and suggests directions for future analyses. First, the suspected relationship between PbD, PbH, and PbB has been confirmed in yet another cohort of children (cf. Bruenekreef *et al.*, 1981; Charney *et al.*, 1980; Roels *et al.*, 1980). Furthermore, the analysis indicates the important interplay between environmental sources of lead and social factors in the determination of hand lead and blood lead levels in very young children. While others (Dietrich *et al.*, 1985; Milar *et al.*, 1980) have shown a relationship between HOME scores and blood lead levels, this study indicates that this relationship is mediated by hand lead.

The discovery of a second pathway between PbD and PbB, while not predicted, is not inexplicable. It is likely that PbD provides better temporal and spatial integration of lead exposure than the more temporally discrete PbH measure. Therefore, the PbD might better reflect general availability of lead for ingestion than does PbH.

The finding that SES remains in the final model and has a direct link with PbB was unexpected. Undoubtedly SES influences PbB via other variables which were not specified in this analysis. It is likely that SES is acting as a surrogate variable for a variable which is more proximate to PbB but unspecified in the present model, e.g., nutritional status. A goal of future analyses is to more completely specify the proximate causal variables such that the SES variable's apparent direct effect on PbB is interpretable as a mediator and not a causal agent.

A review of Table 4 indicates that the variance accounted for (R^2) decreases with the age of the cohort. This suggests that specification error (also referred to as Type III error in the context of multiple regression analyses) is increasing as the child grows older. That is, the model (Fig. 1c) is most appropriate for 9-month-olds and becomes less appropriate or correctly specified as the child grows older. The child's environment is undoubtedly changing with age. PbD is a measurement of lead in surface dust in the interior housing environment. As the child reaches 21 to 24 months of age, lead in the exterior environment should increase in importance since the child is likely to spend more time outside.

Future analyses (see Fig. 1d) will explore a model in which the housing quality variables are replaced with more direct measures of lead in paint, exterior dust, and soil. If these materials are being eaten, they might have a direct impact on PbB over and above that reflected through PbH. As in the case of SES, housing quality is viewed as a variable distal to PbB which should at best explain differences in environmental lead sources, but not internal exposure (PbB).

Further insight into the temporal aspects of the impact of lead sources and social mediators can be gained, in future analyses, through incorporation of prior PbB into the model. This would provide adjustment for past lead exposures and show only the incremental current influence of social/environmental factors on incremental changes in PbB. A determination of when environmental sources and social factors are of greatest importance relative to PbB can then be obtained.

This analysis has demonstrated that structural equation modeling offers a useful approach to unraveling the complex interactions present in a data set of this kind. It also is of heuristic value in ongoing exploratory data analysis and hypothesis generation. It is likely to be of similar value in many other areas of environmental research and warrants the particular attention of those dealing with complex epidemiologic issues.

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